



## Lunar Environment Monitoring Station



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Presented By  
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**TFAWS**  
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Virtual Conference

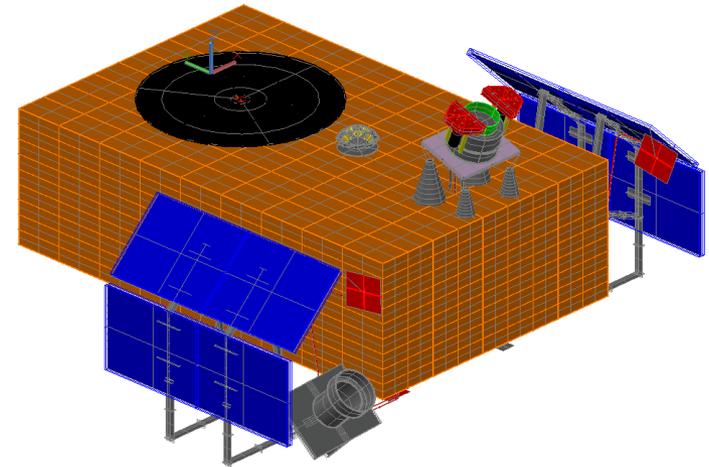


# Presentation Contributors



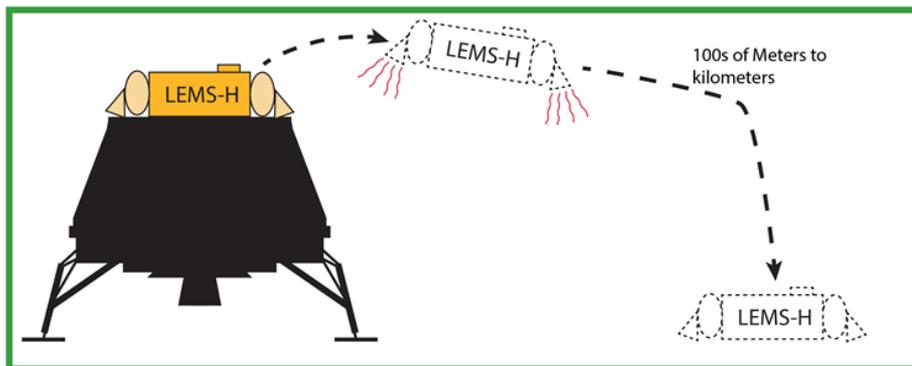
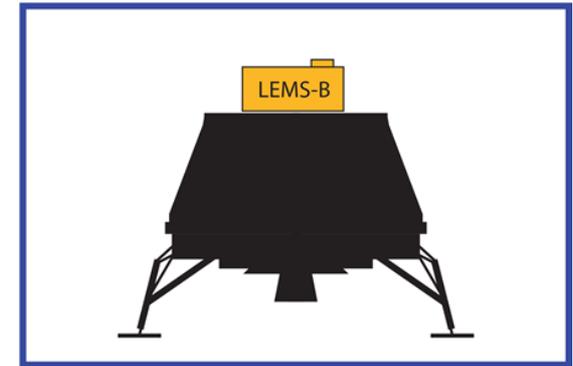
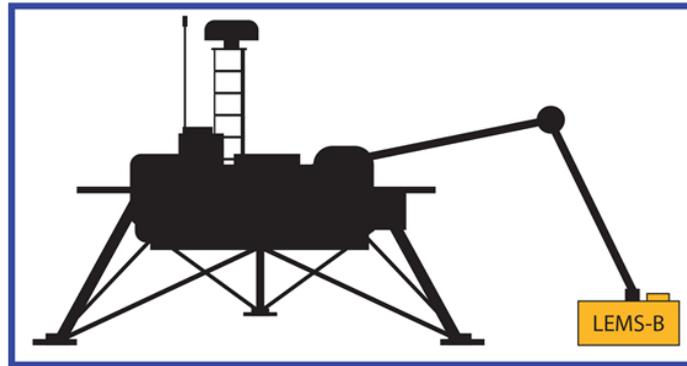
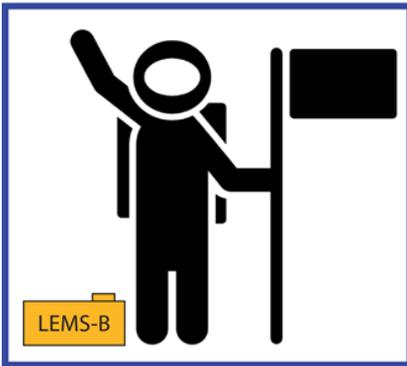
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Contributor, Editor	Principal Investigator	Mehdi Benna
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Contributor	QUEST IMLI	Alan Kopelove
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- LEMS is a compact, autonomous, and self-sustaining instrument package that will enable long-term, in-situ, monitoring of the lunar exosphere and seismic activity for a nominal duration of 2 years from its deployment on the surface of the Moon.
- The station's mass spectrometer will collect daily measurements of exospheric composition.
- The station's seismometer will continuously monitor the Moon's seismic activities in order to constrain the structure of the lunar interior.
- The platform comes in several variants that can accommodate future science goals and mission **scenarios**.

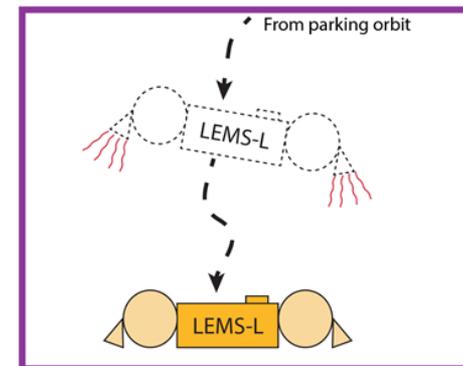


Each variant is built around an identical core spacecraft bus to drive down cost and schedule.

## LEMS-B : Basic Variant

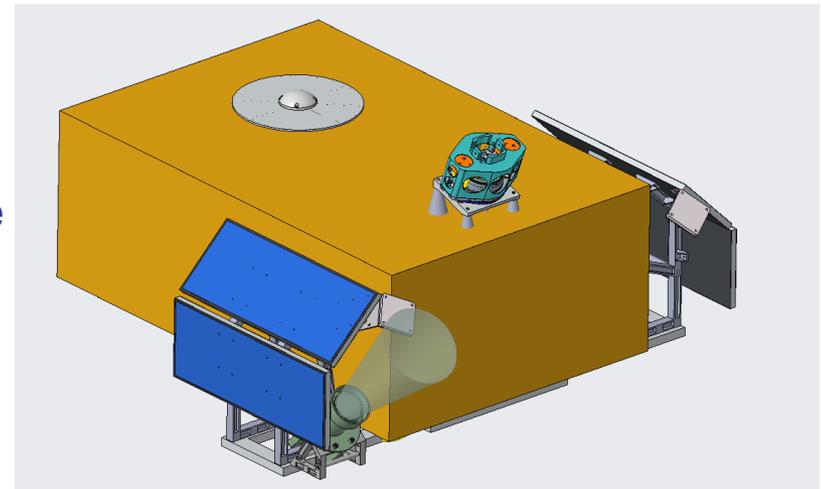


**LEMS-H : Surface Hopper Variant**

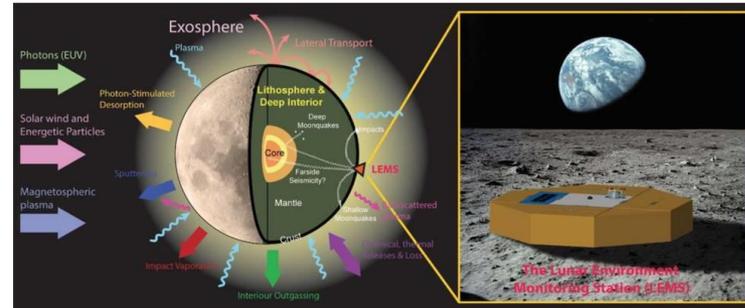
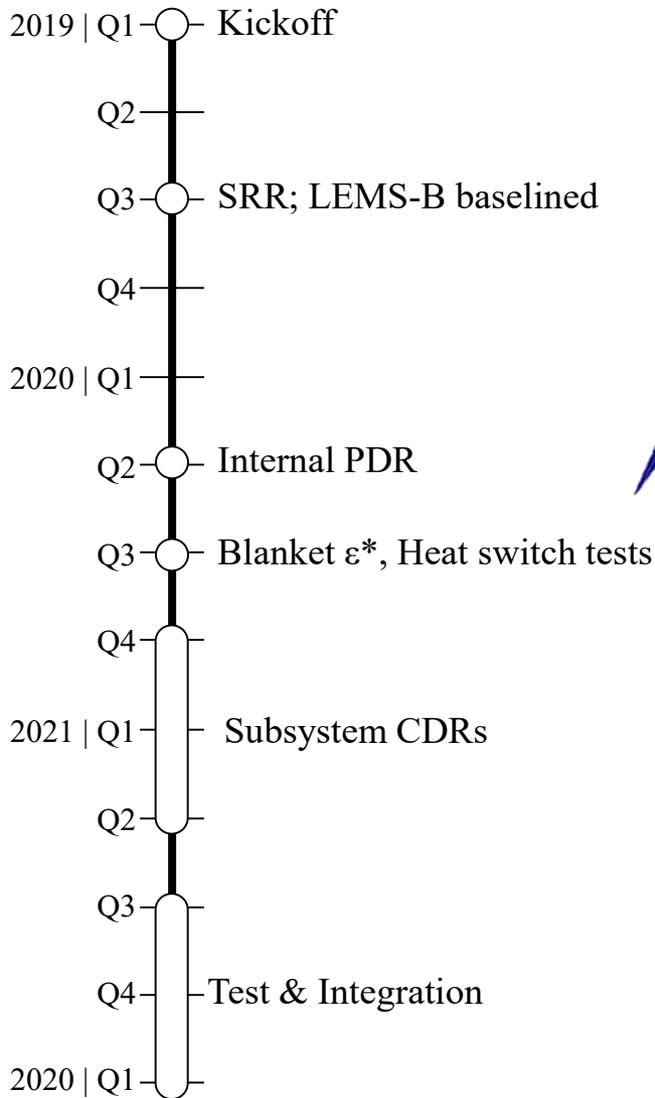


**LEMS-L : Lander Variant**

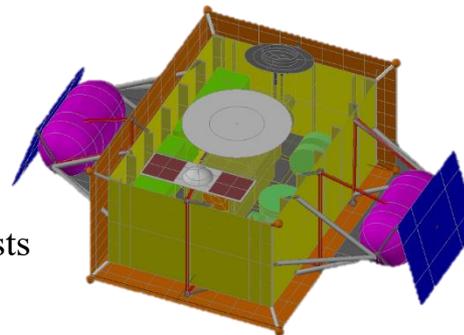
- Development and Advancement of Lunar Instrumentation (DALI) funded TRL-6 development
- Intended augmentation for Commercial Lunar Payload Services (CLPS) landers to allow for continuous day and overnight payload operations for 2 years.
- Internal temperature-controlled payload volume of 0.17 x 0.15 x 0.59 m
- Bounding box of 0.73 x 0.62 x 0.38 m
- Supports transient high power (~50 Watts) and constant low power (<2 Watt) instrumentation
- Current mass CBE of 35 kg
- Current effort baselines latitude of 45° with operational capabilities at other latitudes with design deltas
- Monthly high rate comm links for science data; weekly low rate comm links for telemetry



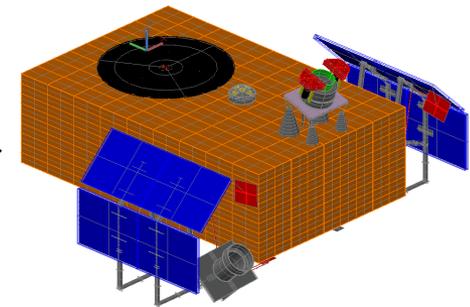
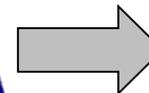
# LEMS Development Timeline



DAI Proposal



SRR Thermal Model



Current Thermal Model



Thermal Blanket Mockup Test Article

## Avionics

### Command and Data Handling

### Hibernation Monitoring System

- Custom processor card for low power data handling

### Special Services Card

- Instrument dependent interface card

## Power

### PSE

### 1000 Whr Li-ion Battery

### Solar Arrays (4)

- Canted to capture morning and evening sun
- Adjusted based on latitude to optimize energy capture

## Payload Instrumentation

### Seismometer

### Mass Spectrometer

- Includes cold trap

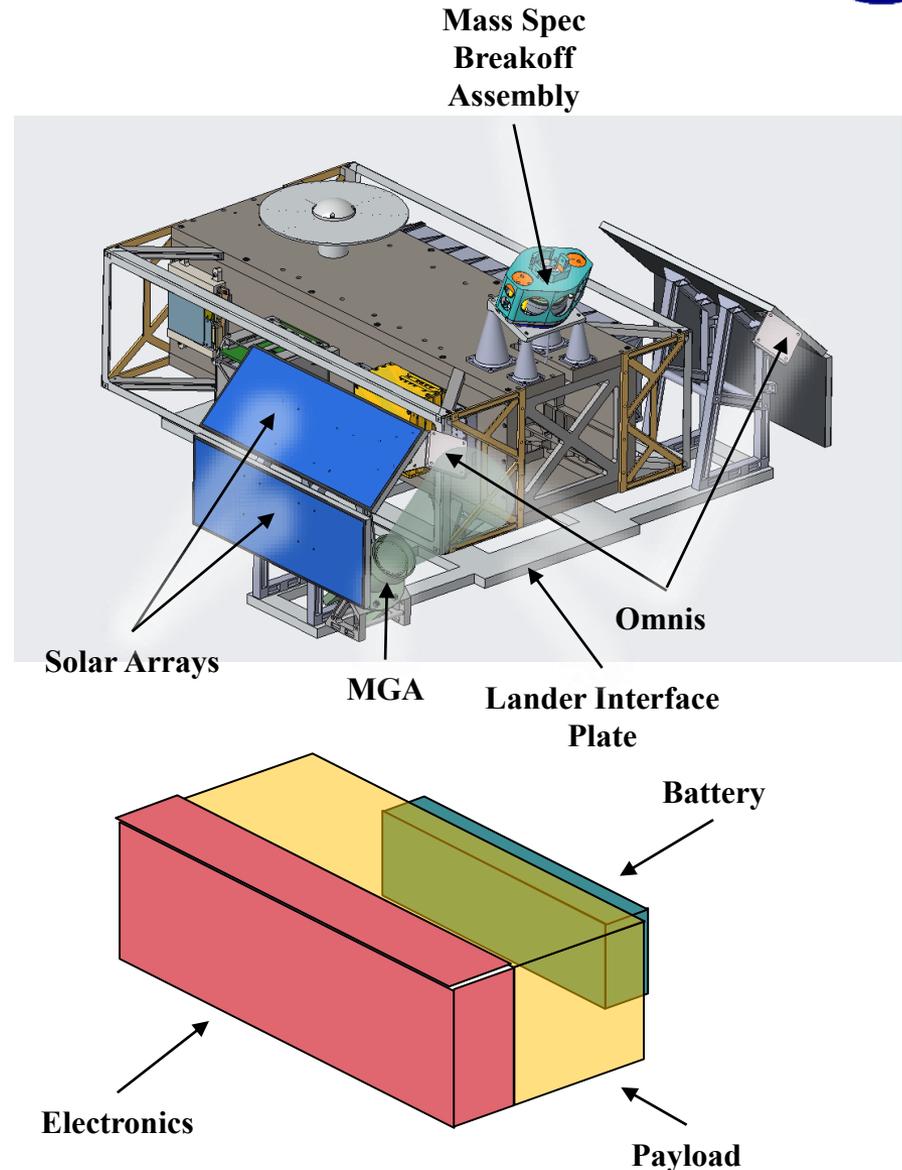
### Retroreflector

## Communications

### X Band Transponder, SSPA, & LNA

### Medium gain antenna return, omni send

- 1 kps uplink
- 256 kps downlink



## Passive Thermal Control

**High efficiency ( $\epsilon^* < 0.0028$ ) MLI Thermal Blanket**

**Variable conductance heat switch + OSR radiator**

- 0.5 W/C On, 0.007 W/C Off

**Optimized interior/exterior optical coatings**

- All black interior to increase interior heat transfer

**Radioisotope Heater Units (RHU) capable**

- Zero baselined
- Use dependent on mission profile

**Low Thermal Conductivity Standoffs**

- Retroreflector standoff
- Mass spectrometer breakoff assembly

## Active Thermal Control

**Cold Op Heaters**

- Operational and survival set points are the same
- Located on electronics panel and battery

**Cold Trap Software-Controlled Heaters**

- Cold trap closes through thermal expansion

**Launch Lock Legs (not shown)**

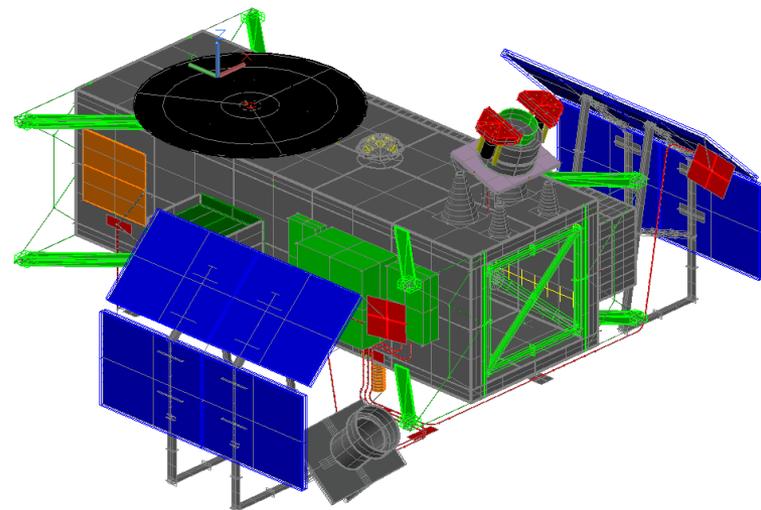
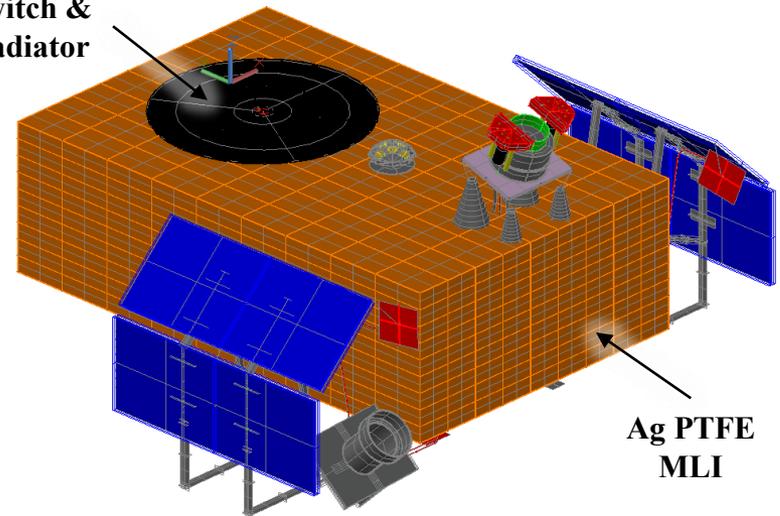
- High strength legs for launch, low thermal conductivity legs for surface operations

## Temperature Telemetry

**Interior components monitored with thermistors**

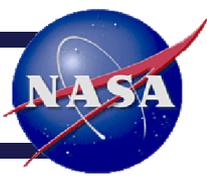
**Exterior components monitored with PRTs**

Heat Switch &  
OSR Radiator





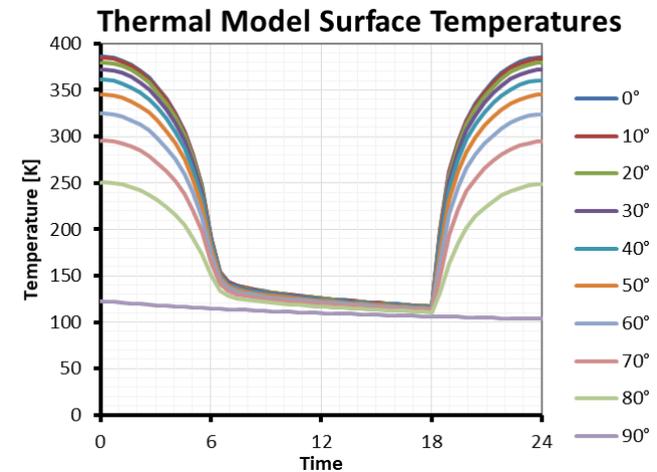
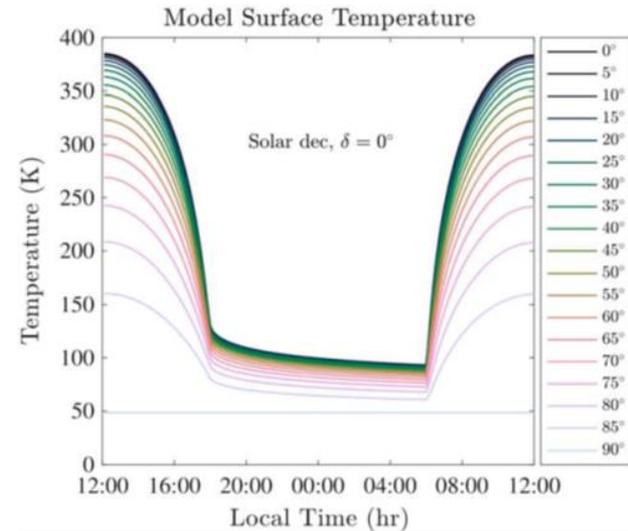
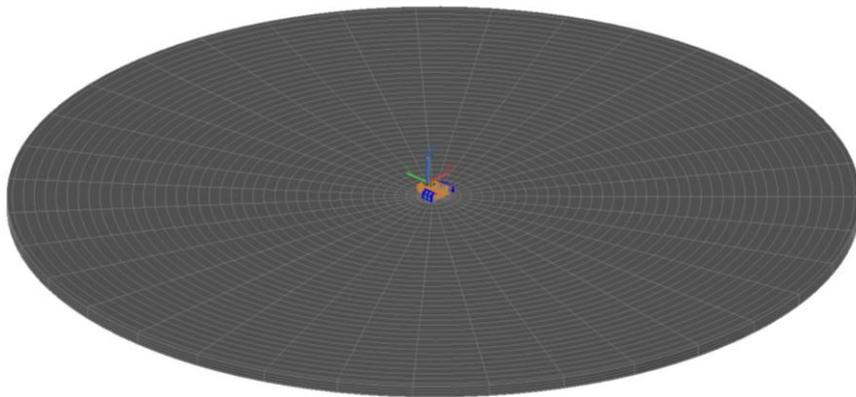
# Heat Loads



Component	Symbol	CBE [W]	MBE [W]	MBE Margin	Hot Case [W]	Night Mult	Night CBE Avg [W]	Night Hot Avg [W]
HMS1 + HMS2	Q_HMS	0.502	0.942	20%	1.130	1.000	0.502	1.130
Seismometer	Q_SEIS	0.150	0.150	5%	0.158	1.000	0.150	0.158
CDH	Q_CDH	1.900	2.270	5%	2.384	0.008	0.016	0.020
PSE	Q_PSE	1.100	1.470	5%	1.544	0.008	0.009	0.013
Transponder	Q_Transponder	15.400	15.400	5%	16.170	0.001	0.017	0.018
SSPA	Q_SSPA	14.700	14.700	5%	15.435	0.001	0.017	0.017
LNA	Q_LNA	0.600	0.600	5%	0.630	0.001	0.001	0.001
<b>LVPC Efficiency</b>		<b>0.900</b>	<b>0.750</b>					
LVPC - HMS	Q_LVPC_HMS	0.056	0.314	20%	0.377	1.000	0.056	0.377
LVPC - Seis	Q_LVPC_Seis	0.017	0.050	5%	0.053	1.000	0.017	0.053
LVPC - CDH	Q_LVPC_CDH	0.211	0.757	5%	0.795	0.008	0.002	0.007
<b>LVPC Subtotal</b>		<b>0.284</b>	<b>1.121</b>		<b>1.224</b>		<b>0.074</b>	<b>0.436</b>
QMS Analyzer	Q_QMS_Analyzer	1.500	1.500	5%	1.575	0.008	0.013	0.013
QMS Control	Q_QMS_ControlPCB	1.600	1.600	5%	1.680	0.008	0.013	0.014
QMS FB	Q_QMS_FillBiasPCB	2.200	2.200	5%	2.310	0.008	0.018	0.019
QMS Power Supply	Q_QMS_PowerPCB	4.100	4.100	5%	4.305	0.008	0.034	0.036
QMS RF Boards	Q_QMS_RFBoards	1.000	1.000	5%	1.050	0.008	0.008	0.009
QMS RF Tank	Q_QMS_RFTank	3.100	3.100	5%	3.255	0.008	0.026	0.027
<b>QMS Subtotal</b>		<b>13.500</b>	<b>13.500</b>		<b>14.175</b>		<b>0.113</b>	<b>0.118</b>
<b>Total</b>		<b>48.136</b>	<b>50.153</b>		<b>52.849</b>		<b>0.898</b>	<b>1.911</b>

Battery Heat Dissipation [W]								
<b>Battery Efficiency</b>		<b>1</b>			<b>0.95</b>			
Battery - Day Nominal	Q_Bat_DayNom	0.000			0.000	0.000	0.000	0.000
Battery - Day Science Op	Q_Bat_DaySciOp	0.000			0.639	0.000	0.000	0.000
Battery - Day Weekly Trans	Q_Bat_DayWeekly	0.000			2.255	0.000	0.000	0.000
Battery - Night Nominal	Q_Bat_NightNom	0.000			0.077	0.990	0.000	0.076
Battery - Night Science Op	Q_Bat_NightSciOp	0.000			1.024	0.008	0.000	0.009
Battery - Night Weekly Trans	Q_Bat_NightWeekly	0.000			2.640	0.001	0.000	0.003
Battery - Monthly Trans	Q_Bat_Monthly	0.000			2.255	0.000	0.000	0.000
Battery - Cold Trap Op	Q_Bat_ColdTrap	0.000			1.211	0.001	0.000	0.001
Total Night Average Heat Loads							0.898	2.000

- Top graph taken from “Global Regolith Thermophysical Properties of the Moon From the Diviner Lunar Radiometer Experiment”; Hayne et. Al
- Bottom graph shows results of Thermal Desktop model of lunar regolith
- Radius of regolith surface is 10m to approximate radiative heat transfer with SC
- Solar Absorptivity at Lat  $45^\circ = 0.6$
- IR Emissivity: 0.78



**(Top) Lunar surface temperatures, Hayne et. Al**

**(Bottom) Thermal Desktop model predicted temperatures**

- Lunar weather measurements at three Apollo sites 1969–1976 from “The Effects of Lunar Dust Accumulation on the Performance of Photovoltaic Arrays”
  - 1 mm/millennium (1  $\mu\text{m}/\text{year}$ ) dust deposition on horizontal surfaces
  - Percent coverage extrapolated from reduction in solar power from the above experiments
    - Worst case solar array lost 1.4% power per year
    - With 50% margin: 2.1% per year
    - Two year mission should expect 4.2% covering of dust
  - Lunar dust optical properties
    - IR emissivity = 0.9
    - Solar Absorptivity = 0.7
  - Optical properties EOL calculated as weighted average of surface properties and dust properties

$$\alpha = \alpha_{EOL}(0.958) + \alpha_{dust}(0.042)$$
$$\epsilon = \epsilon_{EOL}(0.958) + \epsilon_{dust}(0.042)$$



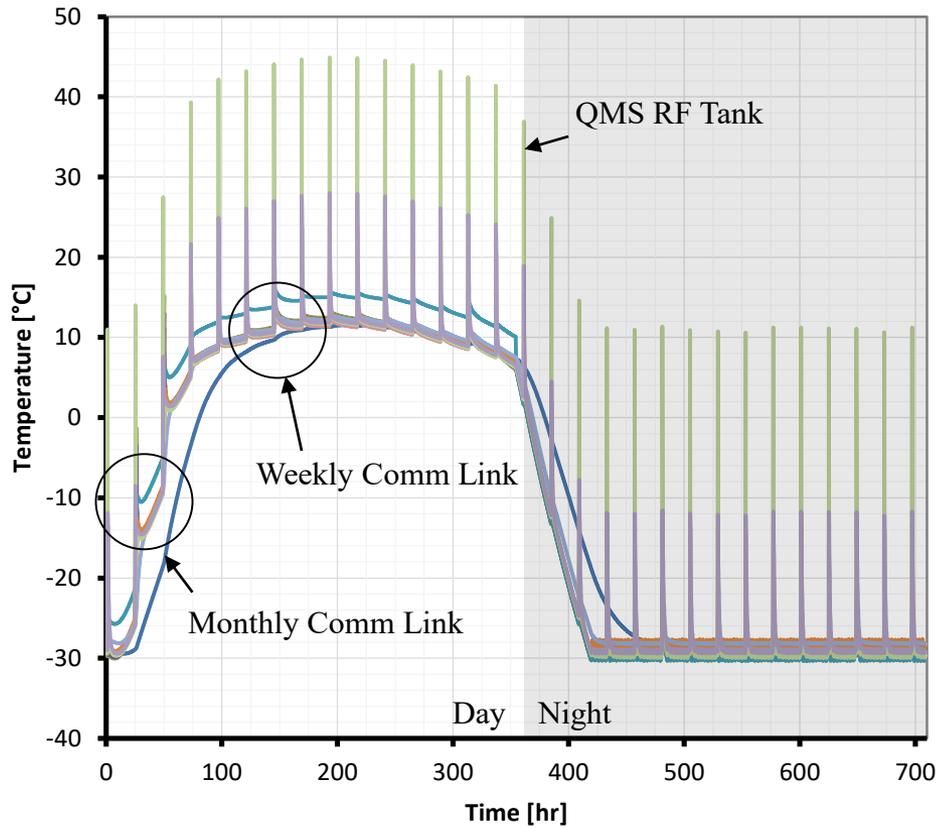
# TRL-6 Thermal Analysis



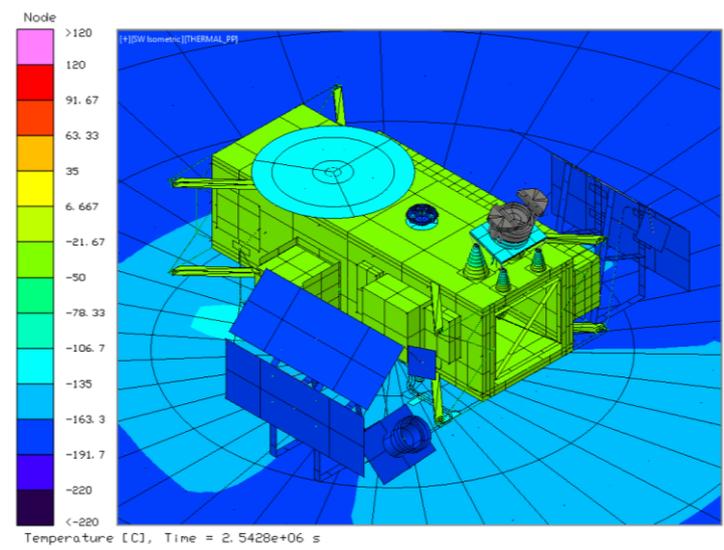
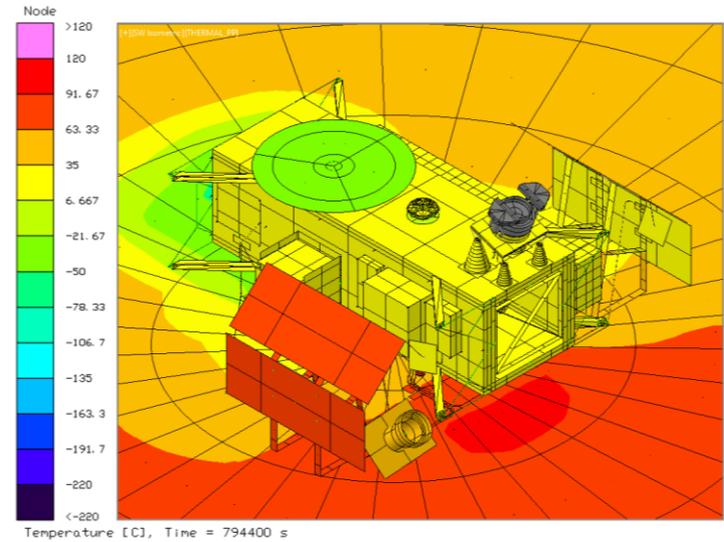
- C&R Tech Thermal Desktop / SINDA Fluintsoftware used to model LEMS
- Environmental conditions, optical properties, and critical interfaces varied between cold and hot cases to bound flight conditions
- Cold Survival has similar environmental conditions to Cold Op but without science instruments operating

Parameter	Cold Surv	Cold Op	Hot Op
Solar Flux [W/m <sup>2</sup> ]	1320	1320	1410
Optical Properties	BOL	BOL	EOL
Dust Accumulation	0%	0%	4.7%
Pitch [deg]	0	0	12
Roll [deg]	0	0	20
Instruments	OFF	ON	ON
Heat Loads	CBE	CBE	MBE

## Cold Op Internal Temperatures

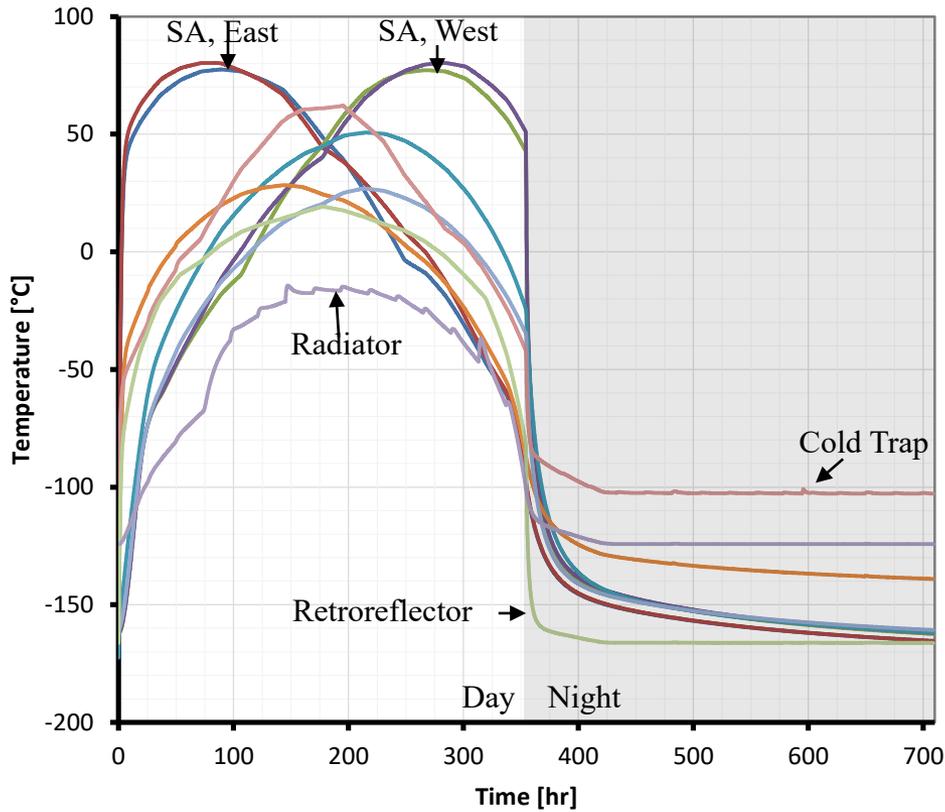


- Battery
- Transponder
- Seismometer
- QMS PSE
- LNA
- PSE
- QMS RF Board
- SSPA
- C&DH
- QMS RF Tank

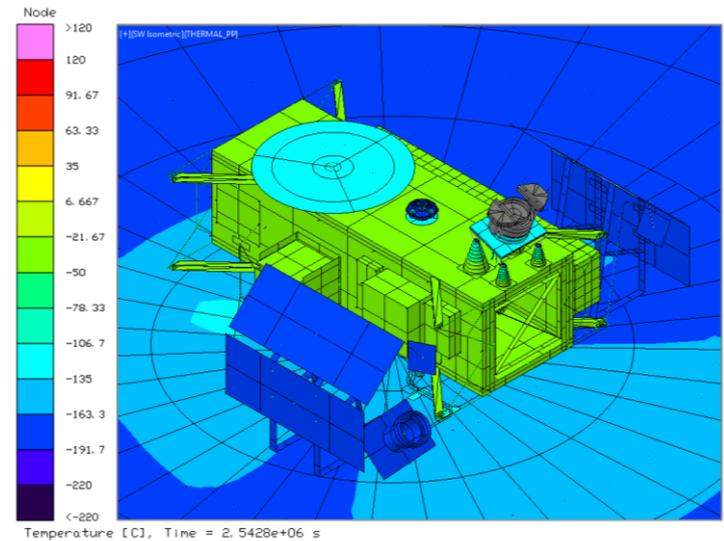
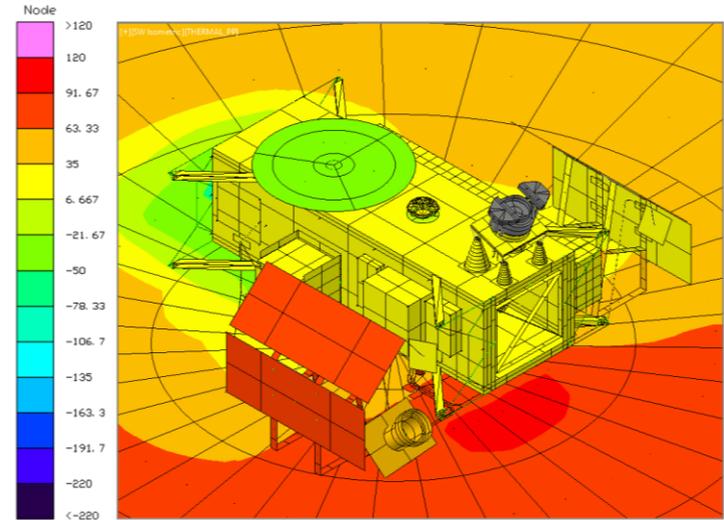


(Top) Max T. (Bottom) Min T

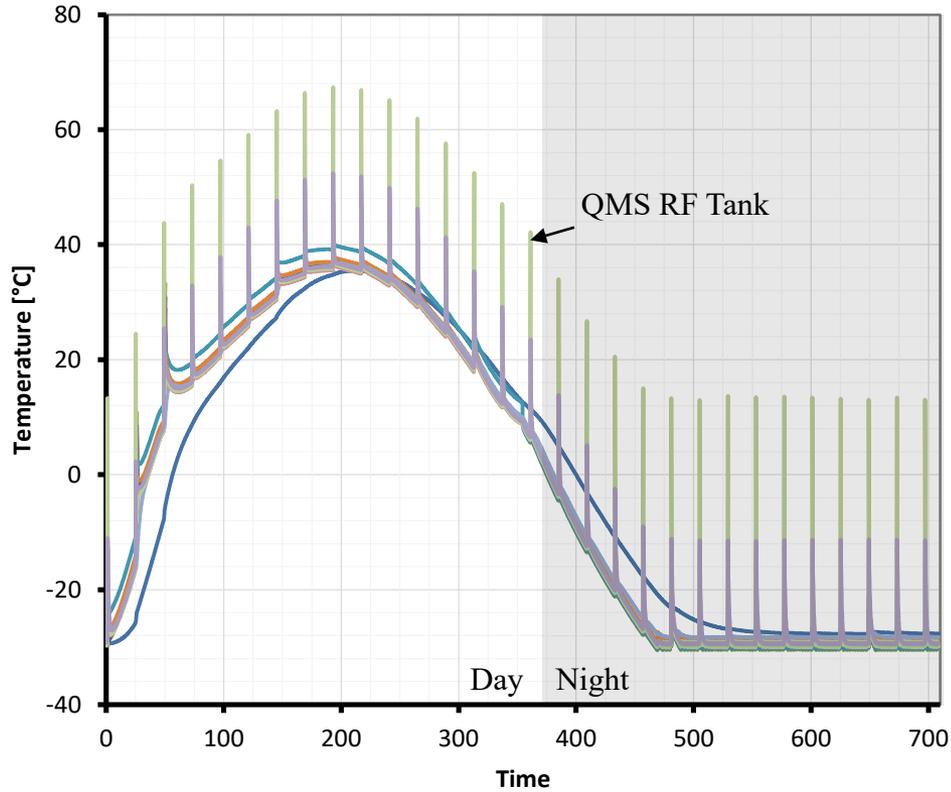
## Cold Op External Temperatures



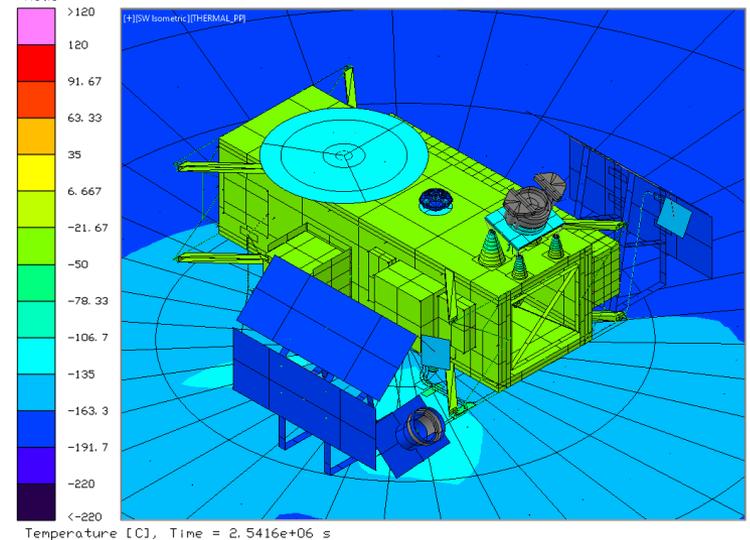
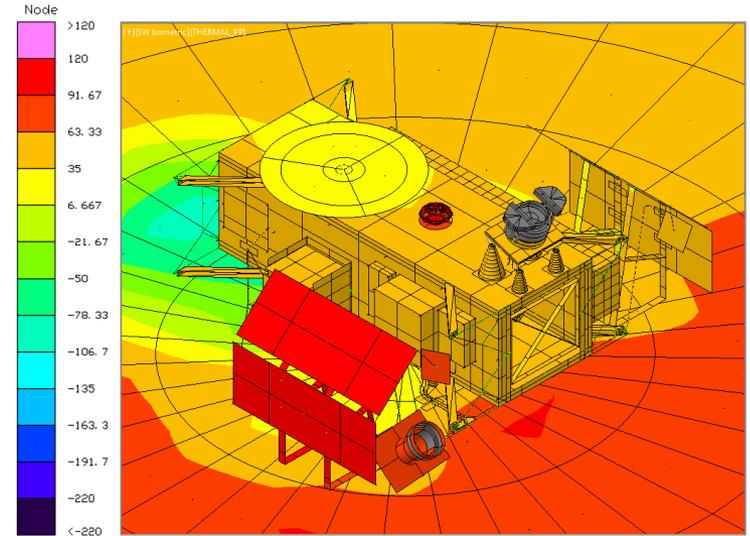
- |                  |            |           |             |
|------------------|------------|-----------|-------------|
| — SA, E90        | — SA, E45  | — SA, W90 | — SA, W45   |
| — MGA            | — Omni, E  | — Omni, W | — Cold Trap |
| — Retroreflector | — Radiator |           |             |



## Hot Op Internal Temperatures

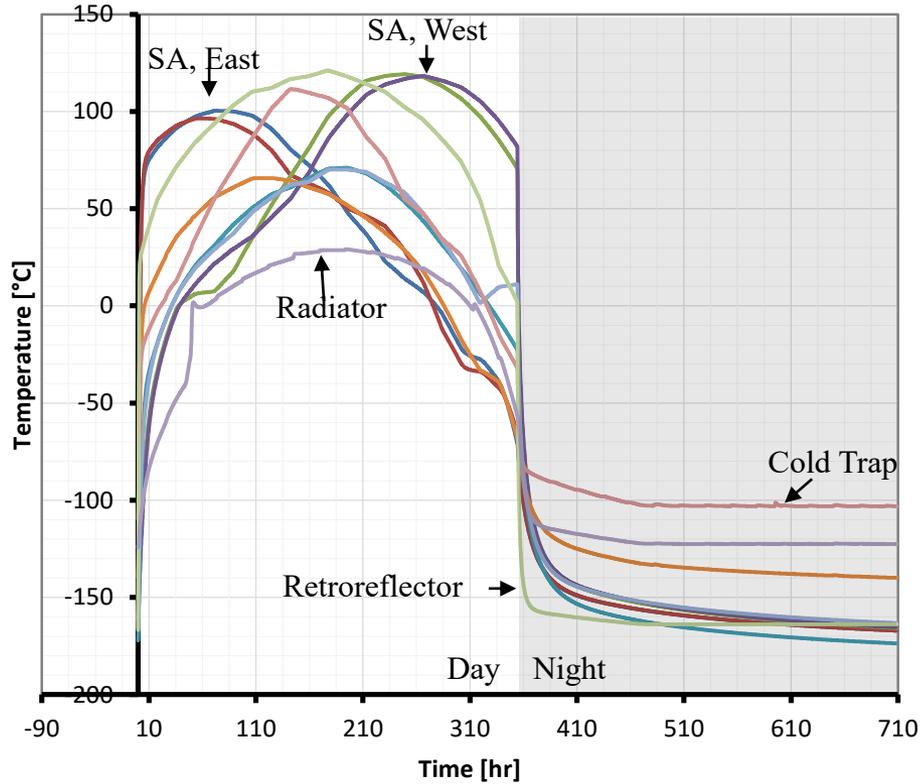


- Battery
- LNA
- SSPA
- Transponder
- PSE
- C&DH
- Seismometer
- QMS RF Board
- QMS RF Tank
- QMS PSE

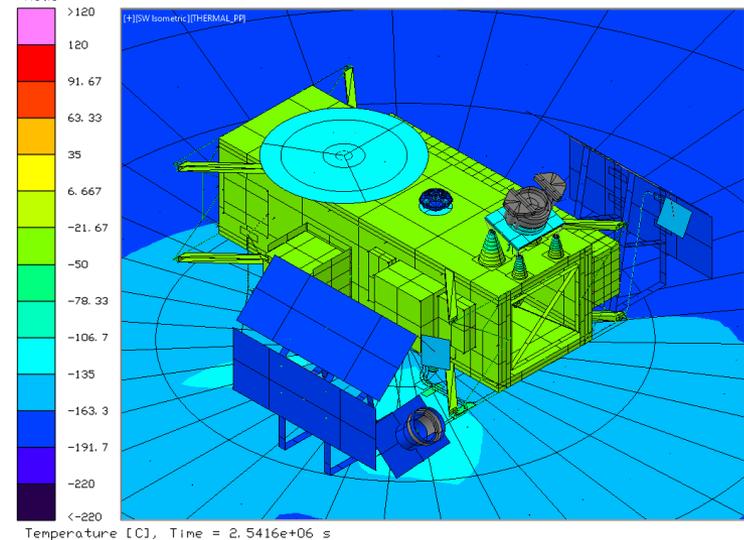
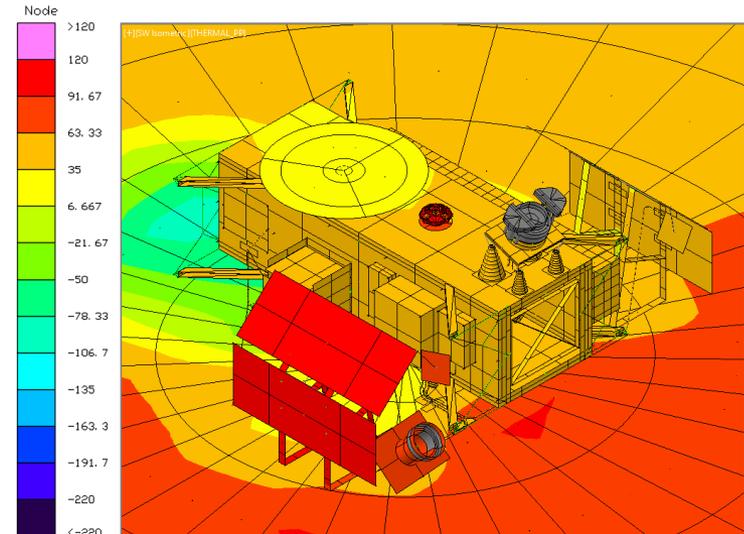


(Top) Max T. (Bottom) Min T

## Hot Op External Temperatures



- SA, E90
- SA, W45
- Omni, W
- Radiator
- SA, E45
- MGA
- Cold Trap
- SA, W90
- Omni, E
- Retroreflector



(Top) Max T. (Bottom) Min T



# Nighttime Heat Flow



- Trade currently being resolved to bring heat leak in line with battery capacity

Averaging Time Start [s] / [hr]		Max Nighttime Heat Leak [W]					Average Nighttime Heat Leak				
		2464992		684.72			1276200		354.5		
Averaging Time End [s] / [hr]		2551392		708.72			2551392		708.72		
Parasitic	Index	QTOT	QLIN	QRAD	QTIE	% Total	QTOT	QLIN	QRAD	QTIE	Total Nighttime Energy Leak [Whr]
BUS_LEG	0	-0.533	-0.533	0.000	0.000	14.4%	-0.501	-0.501	0.000	0.000	-177.6
BUS_BLANKET	1	-0.401	0.000	-0.401	0.000	10.9%	-0.436	0.000	-0.436	0.000	-154.5
BUS_HARNESS	2	-0.437	-0.437	0.000	0.000	11.8%	-0.409	-0.409	0.000	0.000	-145.1
QMS_COLDTRAP_TUBE	3	-0.019	-0.013	-0.005	0.000	0.5%	-0.019	-0.014	-0.006	0.000	-6.9
QMS_TUBE	4	-0.016	-0.014	-0.002	0.000	0.4%	-0.017	-0.014	-0.002	0.000	-5.9
QMS_BREAKOFF_STANDOFFS	5	-0.122	-0.122	0.000	0.000	3.3%	-0.125	-0.125	0.000	0.000	-44.4
QMS_COLDTRAP_HARNESS	6	-0.260	-0.260	0.000	0.000	7.0%	-0.268	-0.268	0.000	0.000	-94.9
RETROREFLECTOR	7	-0.026	-0.026	0.000	0.000	0.7%	-0.027	-0.027	0.000	0.000	-9.6
HEATSWITCH	8	-0.735	-0.735	0.000	0.000	19.9%	-0.756	-0.756	0.000	0.000	-268.1
Omni E Coax	9	-0.372	-0.371	-0.002	0.000		-0.370	-0.369	-0.002	0.000	-131.2
Omni W Coax	10	-0.380	-0.378	-0.002	0.000		-0.377	-0.376	-0.002	0.000	-133.6
MGA Coax	11	-0.393	-0.391	-0.002	0.000		-0.401	-0.399	-0.002	0.000	-142.0
<b>COAX Subtotal</b>	N/A	-1.145	-1.140	-0.005	0.000	31.0%	-1.148	-1.143	-0.005	0.000	-406.8
<b>mCpdT (appr.)</b>											230.0
<b>SUM</b>		-3.695	-3.281	-0.414	0.000		-3.707	-3.258	-0.449	0.000	-1083.7

Battery Capacity [Whr]	-800
Margin	-283.7

# Conclusion

- The LEMS spacecraft is a payload platform that will be capable of operating continuously on the Lunar surface
  - Small design tweaks, i.e. radiator size, solar array angle, can adapt the design to a wider range of latitude
- The TCS is reaching analytical maturity in the near future with TRL-6 testing in late 2021
  - The conclusion of design trades of the communications system is expected to lead to a close of the thermal design.



# References

- C. M. Katzan, D. J. Brinker, and R. Kress, “The Effects of Lunar Dust Accumulation on the Performance of Photovoltaic Arrays,” *Space Photovoltaic Research and Technology Conference*, May 1991.
- P. O. Hayne, J. L. Bandfield, M. A. Siegler, A. R. Vasavada, R. R. Ghent, J.-P. Williams, B. T. Greenhagen, O. Aharonson, C. M. Elder, P. G. Lucey, and D. A. Paige, “Global Regolith Thermophysical Properties of the Moon From the Diviner Lunar Radiometer Experiment,” *Journal of Geophysical Research: Planets*, vol. 122, no. 12, pp. 2371–2400, 2017.

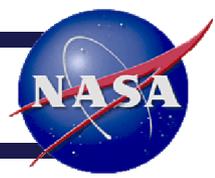
Add reference to LEMS abstract



# BACKUP



# Temperature Limits (1 of 2)



- Platform components isothermal and limited by Li-ion battery
- Platform components are heater controlled

Component	Operational Limits		Qualification Limits		Non-Op Survival Limits	
	Min	Max	Min	Max	Min	Max
Seismometer	-30	70	-35	80	-45	80
Mass Spectrometer	-30	65	-35	75	-45	75
Mass Spectrometer Electronics	-30	50	-35	60	-45	60
Mass Spectrometer Cold Trap	-110	250	-120	260	-120	260
C&DH	-30	50	-35	60	-45	60
Bus PSE	-30	50	-40	60	-45	60
Batteries	-30	40	-35	50	-35	50
Radioisotope Heater Unit (RHU)	N/A					
Solar Array Cells	-220	125	-230	135	-230	135
Solar Array Diodes	-220	110	-230	120	-230	120

Component	Operational Limits		Qualification Limits		Non-Op Survival Limits	
	Min	Max	Min	Max	Min	Max
Omni Antenna	-220	130	-230	130	-230	130
Medium Gain Antenna	-160	110	-170	120	-170	120
Transponder	-30	60	-35	70	-35	70
LNA	-30	60	-35	70	-35	70
SSPA	-30	60	-35	70	-35	70

- Case shown for thermal vacuum chamber test with blanket interior at 35° C and vacuum chamber shroud/platen at -160° C
- Analysis courtesy of Alan Kopelove
- Thermal vacuum emissivity testing just concluded, working on post-processing results

<b>Blanket &amp; penetration heat leak breakdown</b>	<b>MIN Heat Leak [W]</b>	<b>NOM Heat Leak [W]</b>	<b>MAX Heat Leak [W]</b>
<b>MLI Blanket</b>	0.2105	0.2826	0.2868
<b>Penetrations</b>			
<i>Seismometer standoffs, edge effects</i>	0.0004	0.0080	0.0013
<i>Seismometer standoffs, clearance gap</i>	0.0019	0.0122	0.0122
<i>Seismometer wire pass-thru, edge effects</i>	0.0001	0.0007	0.0000
<i>Seismometer wire pass-thru, clearance gap</i>	0.0016	0.0066	0.0073
<i>Radiator standoff, edge effects</i>	0.0006	0.0010	0.0018
<i>Radiator standoff, clearance gap</i>	0.0014	0.0087	0.0087
<i>Bus legs, edge effects</i>	0.0039	0.0038	0.0129
<i>Bus legs, clearance gap</i>	0.0071	0.0446	0.0446
<b>Total estimated heat leak [W]</b>	0.2299	0.3681	0.3814
<b>Total estimated heat flux [W/m<sup>2</sup>]</b>	0.2667	0.4271	0.4425
<b>e* (based on total heat leak)</b>	0.0014	0.0023	0.0024



# Optical Properties



## BOL

## EOL

Name	Solar Absorptivity	IR Emissivity	a/e	Solar Absorptivity	IR Emissivity	a/e
Aluminum, Anodized	0.250	0.890	0.281	0.300	0.700	0.429
Aluminum, Anodized Black	0.730	0.820	0.890	0.840	0.780	1.077
Aluminum, Iridite	0.150	0.190	0.789	0.570	0.060	9.500
BusBlanket_AgTef	0.090	0.870	0.103	0.290	0.830	0.349
BusBlanket_AgTef_pZ	0.090	0.870	0.103	0.310	0.834	0.373
LUNAR	0.700	0.780	0.897	0.700	0.780	0.897
MMOD_1B	0.100	0.025	4.000	0.100	0.025	4.000
MMOD_1T	0.100	0.400	0.250	0.100	0.400	0.250
MMOD_2B	0.100	0.025	4.000	0.100	0.025	4.000
MMOD_2T	0.100	0.400	0.250	0.100	0.400	0.250
OSR	0.100	0.800	0.125	0.244	0.820	0.298
PCB	0.500	0.500	1.000	0.500	0.500	1.000
Retroreflector_Mirror	0.100	0.800	0.125	0.100	0.800	0.125
Silver Teflon Tape, 10 mil	0.090	0.870	0.103	0.290	0.830	0.349
Solar Array, 45	0.660	0.870	0.759	0.788	0.870	0.906
Solar Array, Vertical	0.660	0.870	0.759	0.789	0.870	0.907
Stamet	0.630	0.760	0.829	0.630	0.760	0.829
Steel	0.390	0.150	2.600	0.470	0.110	4.273
Titanium	0.520	0.150	3.467	0.600	0.120	5.000
VDA Kapton	0.080	0.050	1.600	0.080	0.050	1.600
Z307 BLACK PAINT	0.970	0.880	1.102	0.970	0.880	1.102
Z93 White Paint	0.160	0.920	0.174	0.220	0.880	0.250



# Thermophysical Properties



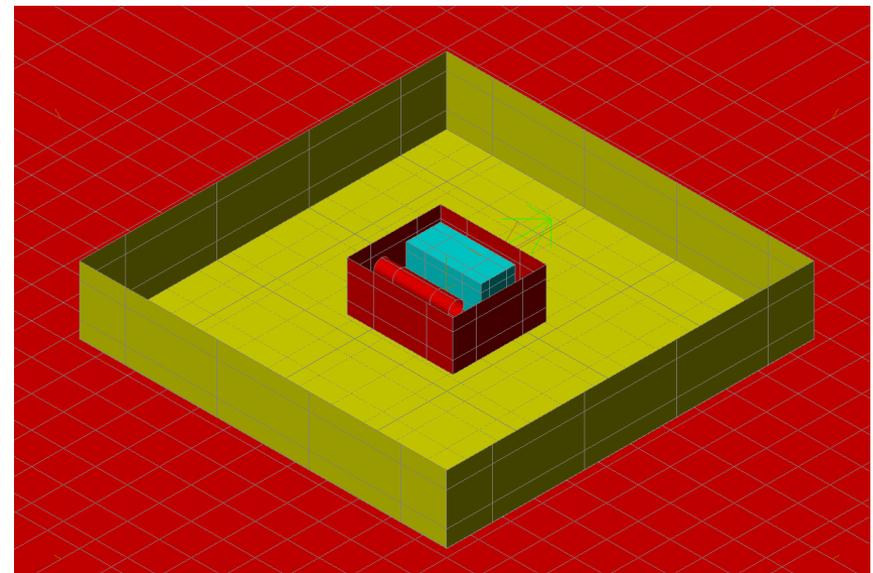
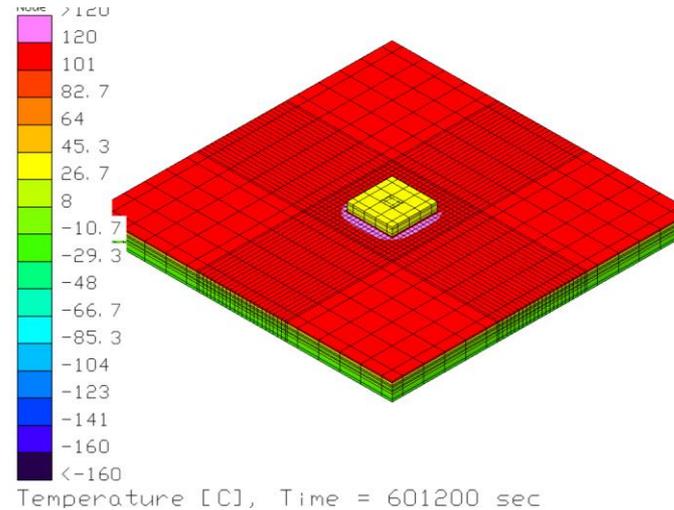
Name	Cond [W/m/C]	Dens [kg/m <sup>3</sup> ]	Cp [J/kg/C]
Al_6061-T6	152.305	2738.6	879.228
Breakoff_Legs	0.249445*	1280	2000
BusBlanket	0	0	0
Copper (RRR 100)	396.482*	8960	387.885*
Copper 99.95	394.45*	8790	390
DEFAULT	1	0	1
G10	0.8	1800	910
Graphite Sheet	1200	2260	720
PCB	39	8660	378
PEEK	0.25	1310	1850
PVDF	0.2	1780	1.6
REGO TEMP DEPEN 0-15cm	0.0101364*	1530	767.521*
REGO TEMP DEPEN 15-30cm	0.00904559*	1630	767.521*
REGO TEMP DEPEN 30cm-10m	0.00904559*	1760	767.521*
Retroreflector_Mirrors	1.38	2200	772
SST304	16.2	8000	500
Ti_6Al4V	7.51356*	4430	521.26*
Ti_AlTape	42	4038	652
Titanium 6AL-4V	7.113	4450	523
ULTEM1000	0.249445*	1280	2000

- Starred (\*) properties are temperature dependent to accurately model heat flow across interfaces with large temperature gradients

- Sensitivity analysis showed that radiator is highly sensitive to changes in solar beta angle and assumed EOL solar absorptivity
- Further discussions with coatings branch led to accepting lower EOL alpha

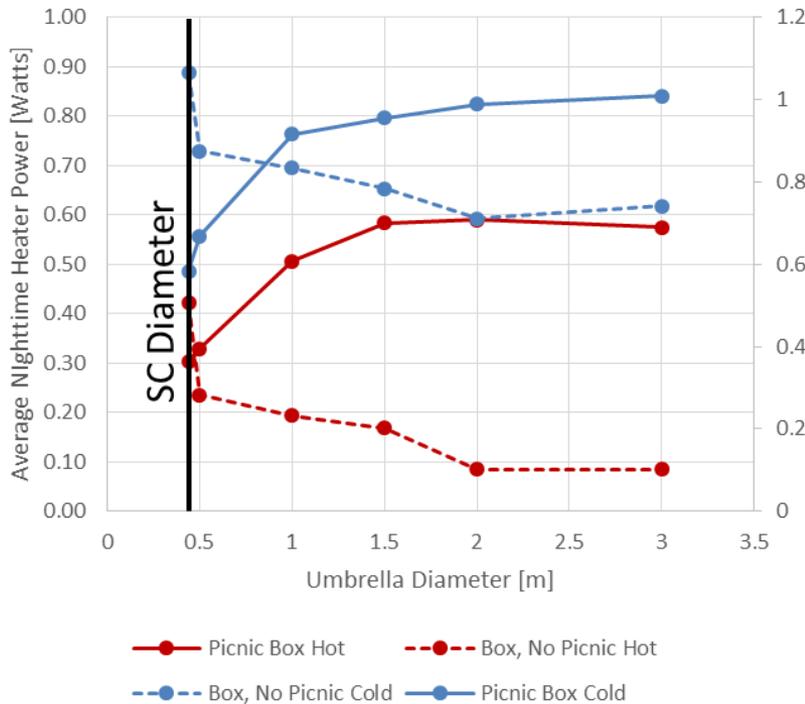
Description	EOL Alpha	Pitch [deg]	Num RHU	RHU Power [W]	SC Dissipation [W]	Radiator Radius [cm]	Radiator Area [cm <sup>2</sup> ]
Baseline, 12° pitch w/ RHU	0.24	12	1.3	1.04	4.5	14.5	661
Trade RHU with battery power	0.24	12	0	0	3.46	12	452
0° pitch for comparison of impact on radiator area	0.24	0	1.3	1.04	4.5	11	380
alpha = 0.2, w/ RHU	0.2	12	1.3	1.04	4.5	10.95	377
alpha = 0.2, w/o RHU	0.2	12	0	0	3.46	9.6	290

- Sensativity analysis of umbrella style thermal blanket deployed over the regolith
  - Idea aimed to incorporate regolith as a temperature regulating thermal mass
  - Alternative operating principle would be to “tap into” constant temperature layer 5 to 15 cm below surface
  - Idea descoped due to mass, complexity, uncertainty in operating principle, and variability in deployment

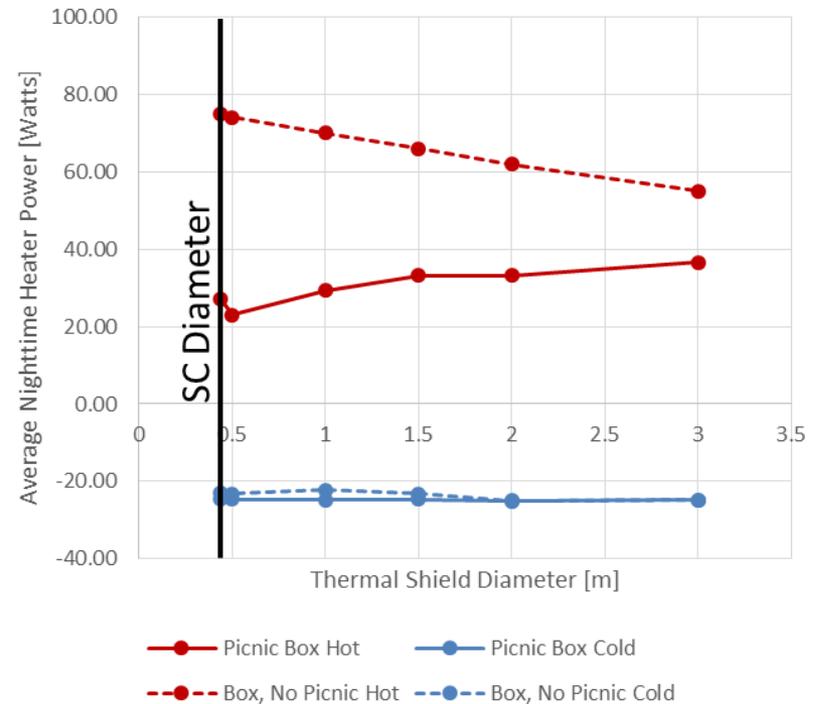


- The box w/o picnic blanket requires a diameter of 2.5 meters to meet temperature limits and to match the performance of the box w/ picnic blanket

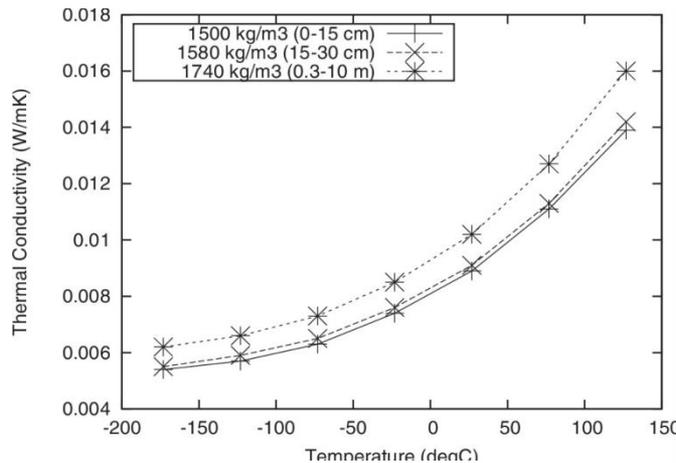
Full Thermal Shield vs. w/o Regolith-facing Blanket Average Nighttime Heater Power



Full Thermal Shield vs. w/o Regolith-facing Blanket Max Temperature



- Global Regolith Thermophysical Properties of the Moon From the Diviner Lunar Radiometer Experiment; Hayne et. Al



**Table 1**  
Constraints on Lunar Regolith Density Profiles

Depth range (m)	Density (kg m <sup>-3</sup> )	
	Apollo in situ <sup>a</sup>	This study
0-0.15	1,500 ± 50	1,530 ± 100
0-0.30	1,580 ± 50	1,630 ± 50
0.30-0.60	1,740 ± 50	1,790 ± 10
0-0.60	1,660 ± 50	1,710 ± 50

Note. Error bars on the values derived in this study correspond to the 1σ range in fits to the Diviner data.

<sup>a</sup>Mitchell et al., 1973.

Specific heat capacity

Coefficients for specific heat capacity function

$$c_p = c_0 + c_1 T + c_2 T^2 + c_3 T^3 + c_4 T^4$$

$c_0 = -3.6125 \text{ J kg}^{-1} \text{ K}^{-1}$   
 $c_1 = +2.7431 \text{ J kg}^{-1} \text{ K}^{-2}$   
 $c_2 = +2.3616 \times 10^{-3} \text{ J kg}^{-1} \text{ K}^{-3}$   
 $c_3 = -1.2340 \times 10^{-5} \text{ J kg}^{-1} \text{ K}^{-4}$   
 $c_4 = +8.9093 \times 10^{-9} \text{ J kg}^{-1} \text{ K}^{-5}$